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Tiwari et al.

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(54) **SYSTEM AND METHOD FOR NUMERICALLY EVALUATING THERMAL COMFORT INSIDE AN ENCLOSURE**

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(30) **Foreign Application Priority Data**

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(51) **Int. Cl.**
G06G 7/48 (2006.01)

(52) **U.S. Cl.** **703/6**

(58) **Field of Classification Search** ..... 703/2, 6, 703/7; 706/45; 236/49.3, 44 C; 700/276; 702/50; 374/109
See application file for complete search history.

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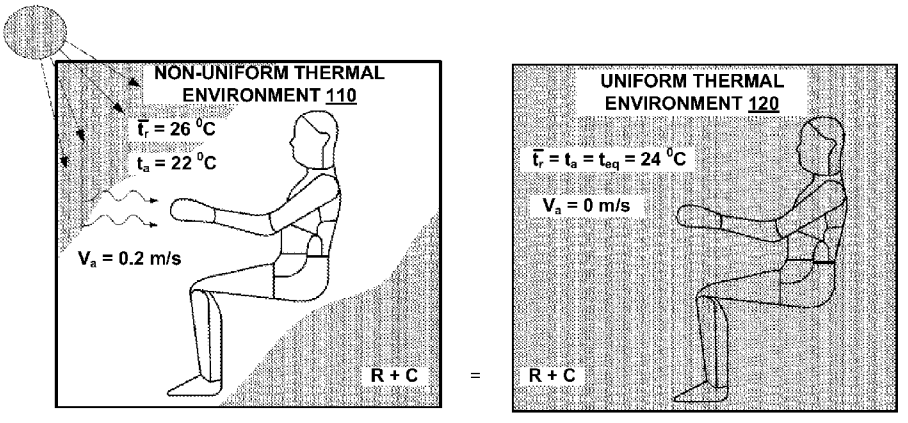
(57) **ABSTRACT**

A system and method for assessing thermal comfort in an enclosure is disclosed. In one embodiment, a method includes performing a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin. The method also includes performing a numerical analysis on an enclosure including one or more thermal manikins in a non-uniform thermal environment to obtain a total heat flux (q''_T) for each body part of the one or more thermal manikins. The method further includes computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins using the obtained associated h_{cal}, the obtained associated q''_T, and an associated surface temperature of the body part. Furthermore, the method includes evaluating thermal comfort in the enclosure based on each computed t_{eq}.

25 Claims, 7 Drawing Sheets



100

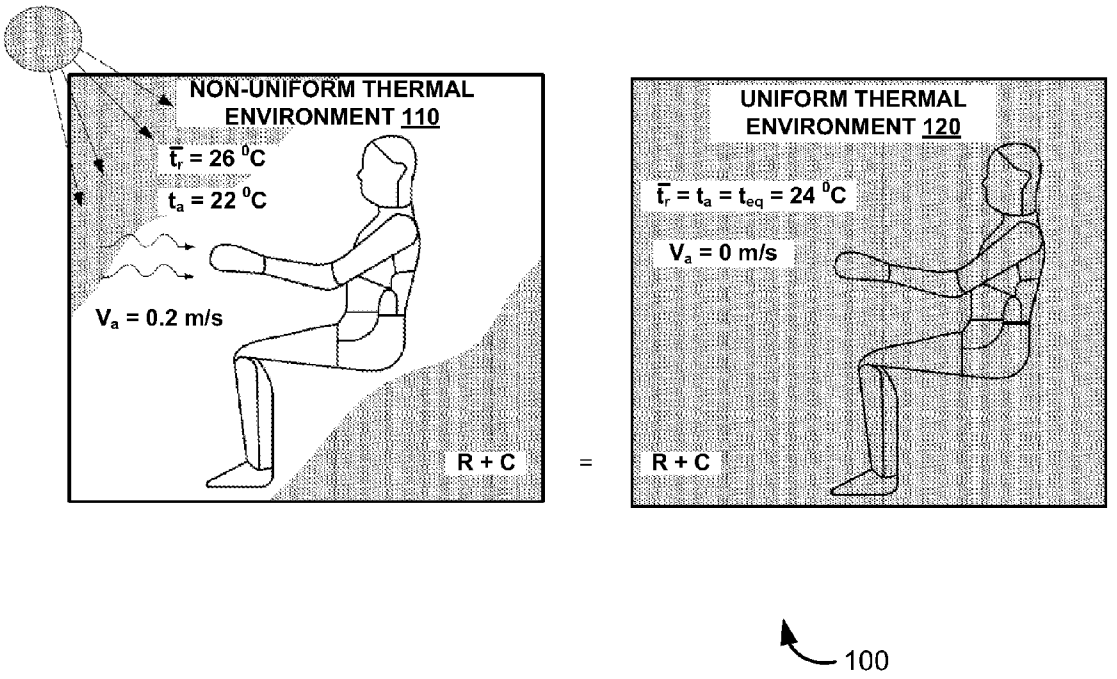

NON-UNIFORM THERMAL ENVIRONMENT 110
$\bar{t}_r$ = 26 °C
t_a = 22 °C
V_a = 0.2 m/s
R + C
=
UNIFORM THERMAL ENVIRONMENT 120
$\bar{t}_r = t_a = t_{eq}$ = 24 °C
V_a = 0 m/s
R + C
100

FIG. 1

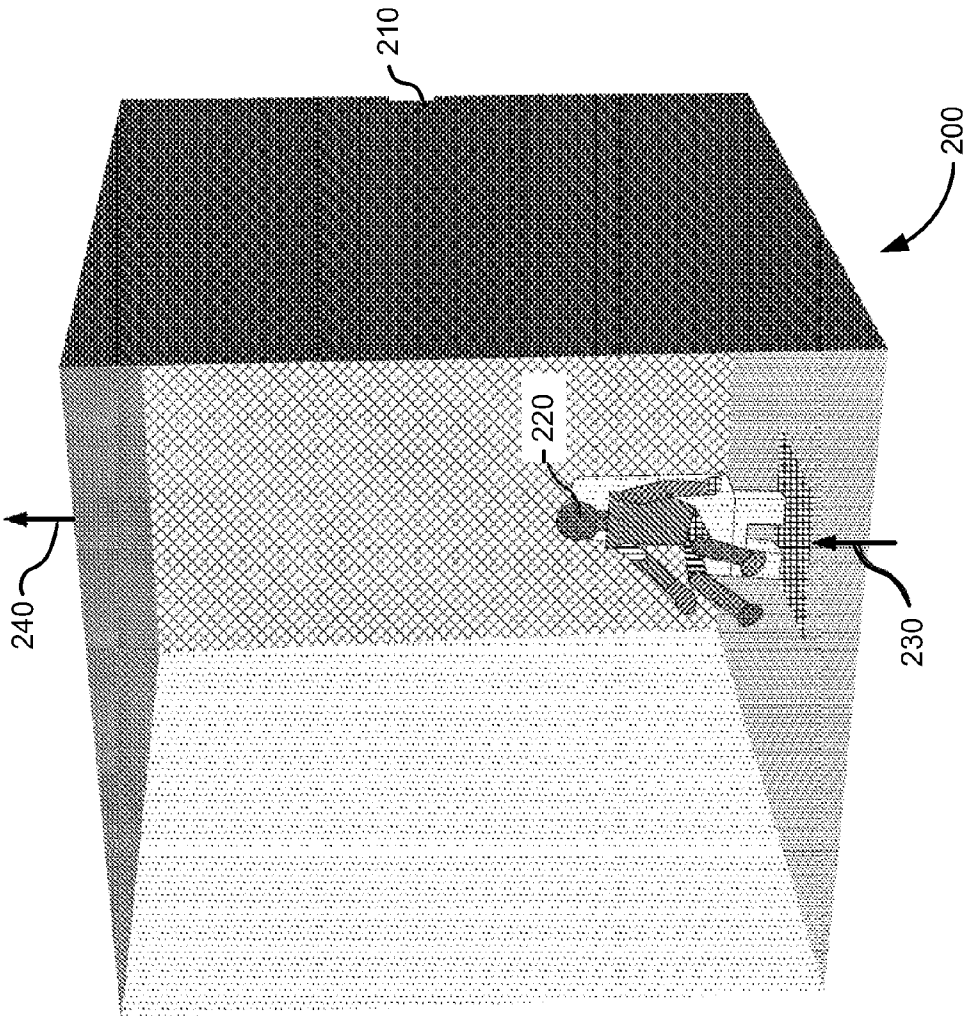


FIG. 2

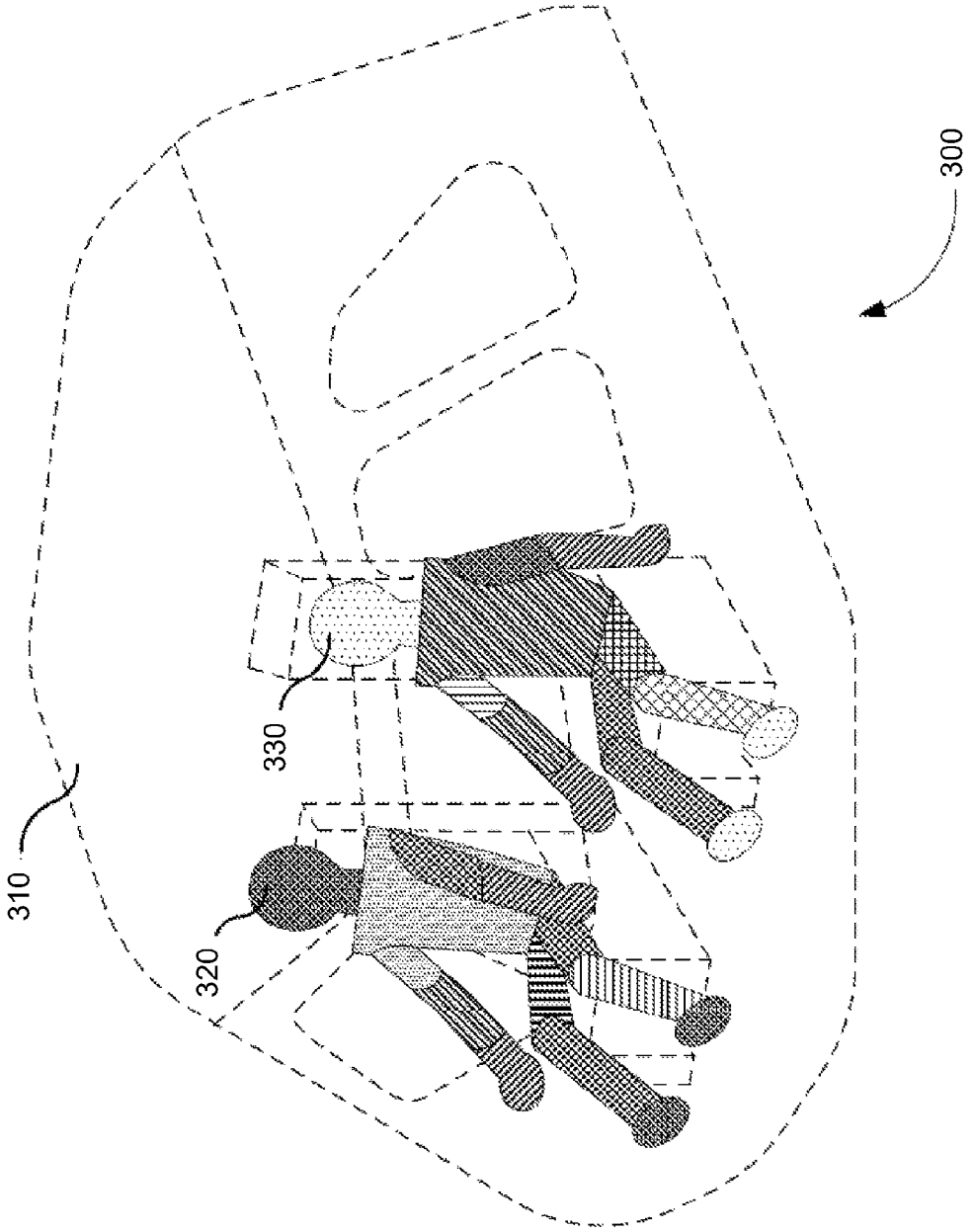


FIG. 3

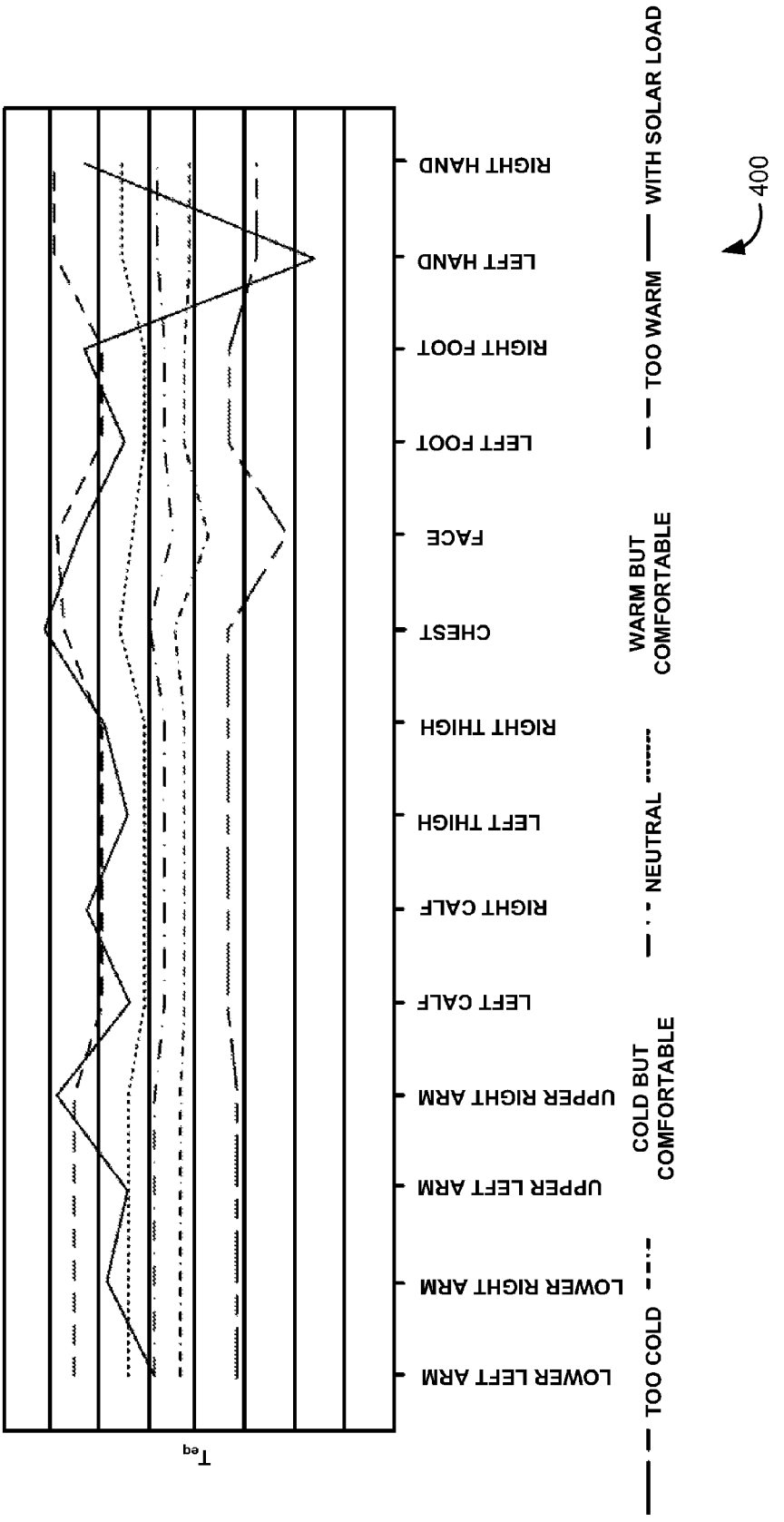

400
WITH SOLAR LOAD
TOO WARM
WARM BUT COMFORTABLE
NEUTRAL
COLD BUT COMFORTABLE
TOO COLD
RIGHT HAND
LEFT HAND
RIGHT FOOT
LEFT FOOT
FACE
CHEST
RIGHT THIGH
LEFT THIGH
RIGHT CALF
LEFT CALF
UPPER RIGHT ARM
UPPER LEFT ARM
LOWER RIGHT ARM
LOWER LEFT ARM
T_{eq}

FIG. 4A

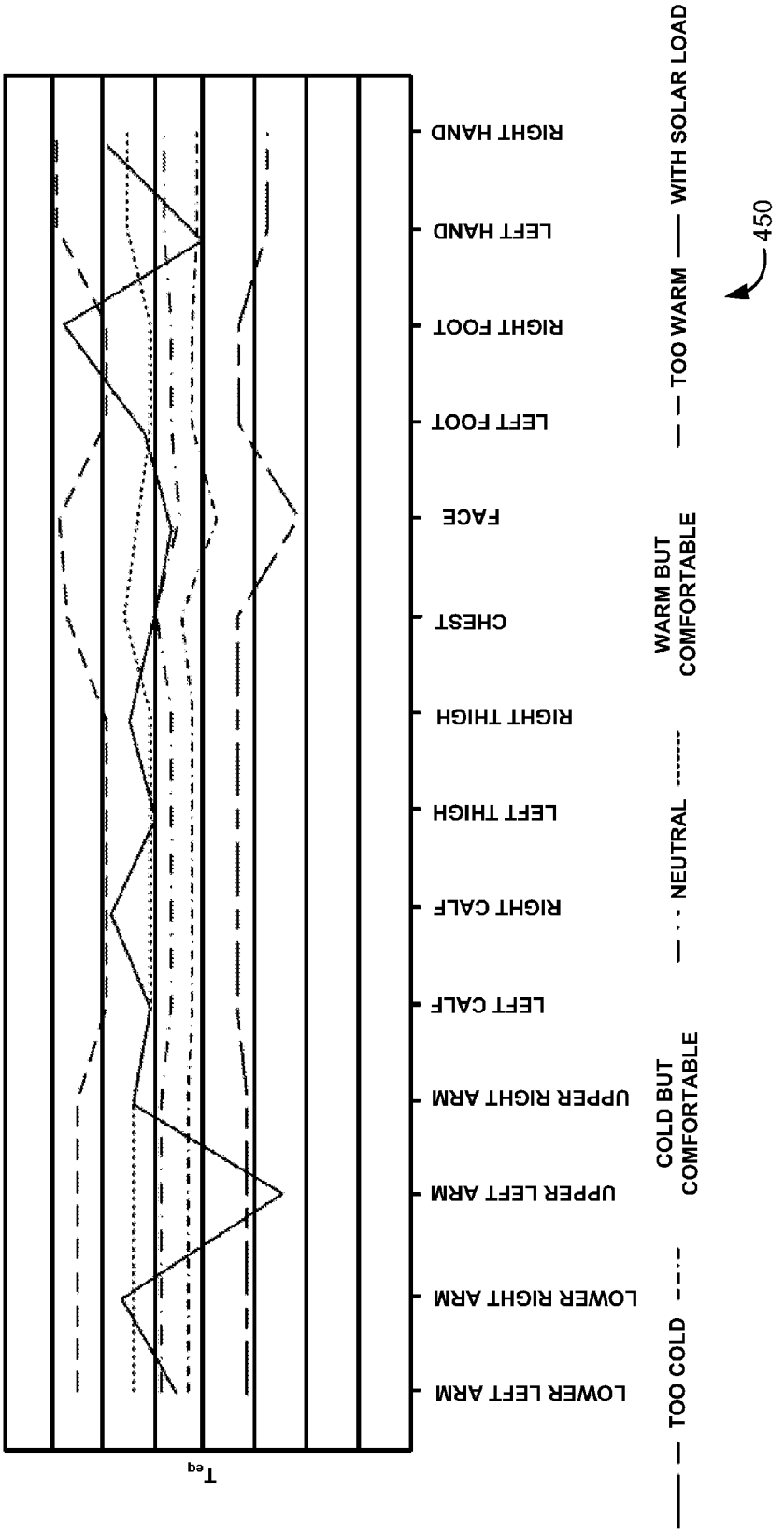

RIGHT HAND
LEFT HAND
RIGHT FOOT
LEFT FOOT
FACE
CHEST
RIGHT THIGH
LEFT THIGH
RIGHT CALF
LEFT CALF
UPPER RIGHT ARM
UPPER LEFT ARM
LOWER RIGHT ARM
LOWER LEFT ARM
T_{eq}
TOO COLD
COLD BUT COMFORTABLE
NEUTRAL
WARM BUT COMFORTABLE
TOO WARM
WITH SOLAR LOAD
450

FIG. 4B

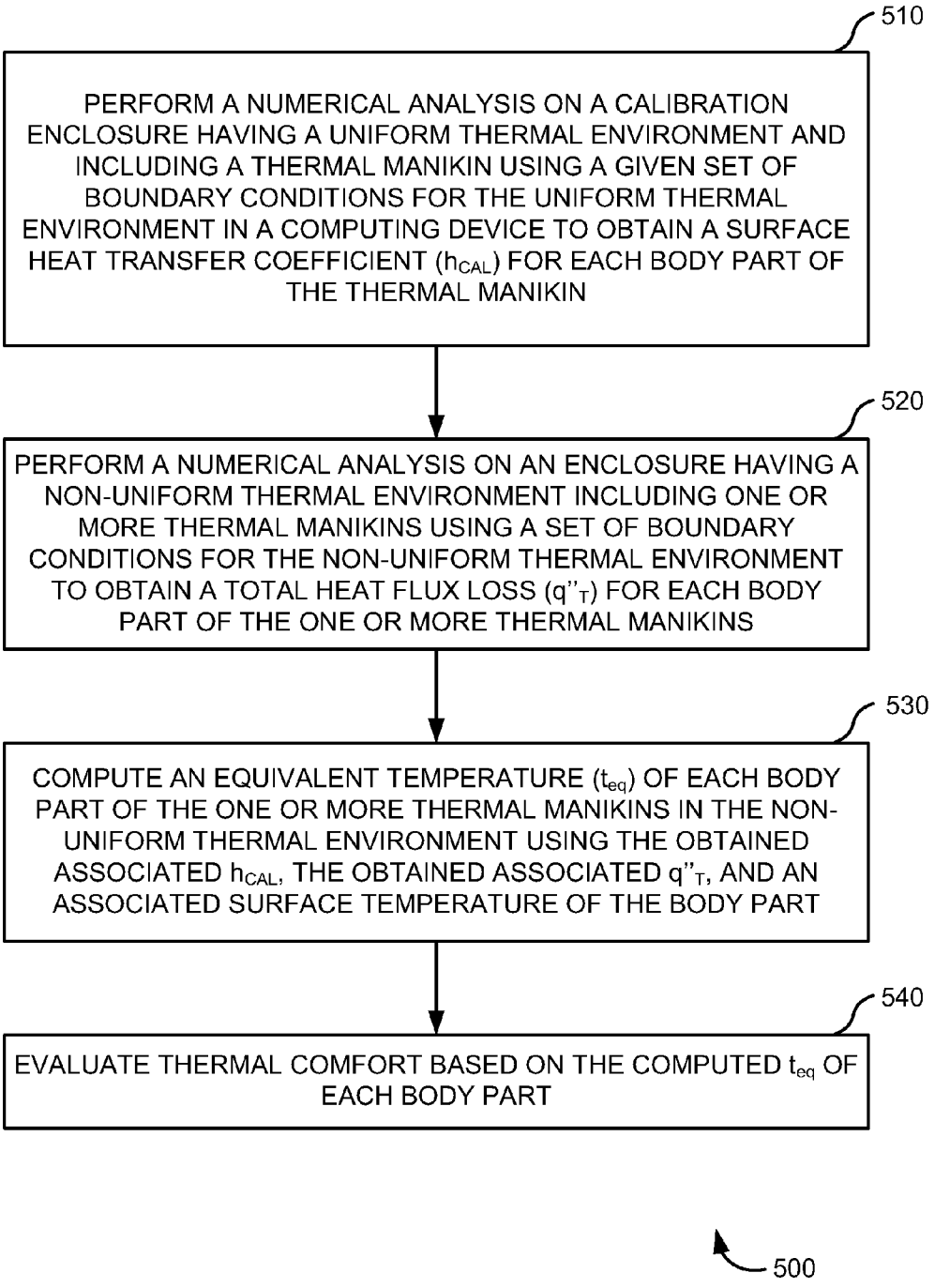

510
PERFORM A NUMERICAL ANALYSIS ON A CALIBRATION ENCLOSURE HAVING A UNIFORM THERMAL ENVIRONMENT AND INCLUDING A THERMAL MANIKIN USING A GIVEN SET OF BOUNDARY CONDITIONS FOR THE UNIFORM THERMAL ENVIRONMENT IN A COMPUTING DEVICE TO OBTAIN A SURFACE HEAT TRANSFER COEFFICIENT (h_{CAL}) FOR EACH BODY PART OF THE THERMAL MANIKIN
520
PERFORM A NUMERICAL ANALYSIS ON AN ENCLOSURE HAVING A NON-UNIFORM THERMAL ENVIRONMENT INCLUDING ONE OR MORE THERMAL MANIKINS USING A SET OF BOUNDARY CONDITIONS FOR THE NON-UNIFORM THERMAL ENVIRONMENT TO OBTAIN A TOTAL HEAT FLUX LOSS (q''_T) FOR EACH BODY PART OF THE ONE OR MORE THERMAL MANIKINS
530
COMPUTE AN EQUIVALENT TEMPERATURE (t_{eq}) OF EACH BODY PART OF THE ONE OR MORE THERMAL MANIKINS IN THE NON-UNIFORM THERMAL ENVIRONMENT USING THE OBTAINED ASSOCIATED h_{CAL}, THE OBTAINED ASSOCIATED q''_T, AND AN ASSOCIATED SURFACE TEMPERATURE OF THE BODY PART
540
EVALUATE THERMAL COMFORT BASED ON THE COMPUTED t_{eq} OF EACH BODY PART
500

FIG. 5

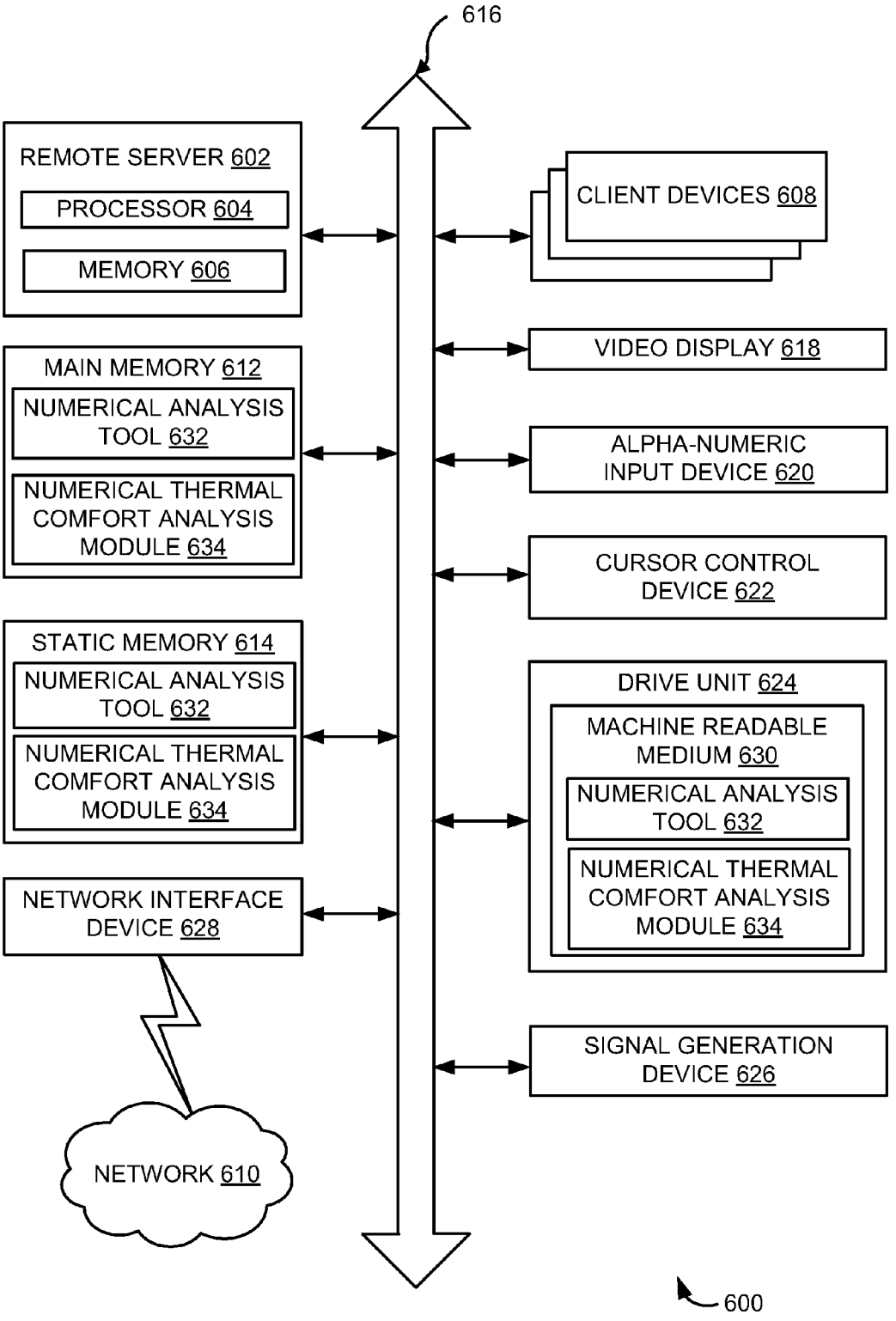

616
REMOTE SERVER 602
PROCESSOR 604
MEMORY 606
MAIN MEMORY 612
NUMERICAL ANALYSIS TOOL 632
NUMERICAL THERMAL COMFORT ANALYSIS MODULE 634
STATIC MEMORY 614
NUMERICAL ANALYSIS TOOL 632
NUMERICAL THERMAL COMFORT ANALYSIS MODULE 634
NETWORK INTERFACE DEVICE 628
NETWORK 610
CLIENT DEVICES 608
VIDEO DISPLAY 618
ALPHA-NUMERIC INPUT DEVICE 620
CURSOR CONTROL DEVICE 622
DRIVE UNIT 624
MACHINE READABLE MEDIUM 630
NUMERICAL ANALYSIS TOOL 632
NUMERICAL THERMAL COMFORT ANALYSIS MODULE 634
SIGNAL GENERATION DEVICE 626
600

FIG. 6

SYSTEM AND METHOD FOR NUMERICALLY EVALUATING THERMAL COMFORT INSIDE AN ENCLOSURE

RELATED APPLICATIONS

Benefit is claimed under 35 U.S.C. 119(a)-(d) to India Non-Provisional application with Serial No.1665/CHE/2009 entitled "SYSTEM AND METHOD FOR NUMERICALLY EVALUATING THERMAL COMFORT INSIDE AN ENCLOSURE" by Airbus Engineering Centre India and Airbus Operations GmbH filed on 14 Jul., 2009, which is herein incorporated in its entirety by reference for all purposes.

FIELD OF TECHNOLOGY

The present invention relates generally to numerical simulations, and more particularly relates to numerical simulations to evaluate thermal comfort inside an enclosure.

BACKGROUND

Typically, a thermal environment inside an enclosure, such as a building, a vehicle or a cockpit of an aircraft, largely depends on parameters such as velocities, temperatures inside the enclosure, solar irradiation incident through a window glass and the like. For assessing thermal comfort inside an enclosure, it is necessary to evaluate the influence of the above-mentioned parameters on thermal sensation that an occupant actually feels inside the enclosure. Traditionally, thermal comfort assessment is performed through a predicted mean vote (PMV) approach as outlined in international organization for standardization (ISO) 7730 standards.

However, drawbacks with the PMV approach are that it is typically applicable under uniform and homogeneous conditions and it depends very much on empirical correlations which are based on various parameters (e.g., velocity, temperature, etc.). In summary, using the PMV approach in non-uniform thermal environmental conditions (that typically exist in aircrafts, vehicles and the like due to air velocity, differences between air and wall temperature and solar irradiation) may lead to incorrect prediction of the thermal comfort assessment.

Another conventional approach based on equivalent temperature (t_{eq}), as outlined in ISO 14505-2 standards, is an integrated measure of the effects of non-evaporative (dry) heat loss from a body of an occupant. The equivalent temperature (t_{eq}) refers to a temperature of an imaginary enclosure having a mean radiant temperature equal to an air temperature and still air in which an occupant has the same heat exchange rate by convection and radiation as in the actual conditions. As outlined in the ISO 14505-2 standards, t_{eq} is typically calculated either using an empirical formula or through experiments. However, using the empirical formula may not be sensitive to changes in the physical parameters around the occupant inside the enclosure and may not yield actual t_{eq} of the body of the occupant. Also, calculating t_{eq} experimentally requires using thermal manikins (e.g., dummy dolls for reproducing thermal characteristics of occupants) and this may often be limited by cost, time and accurate representations of the actual conditions inside the enclosure.

SUMMARY

A system and method for numerically evaluating thermal comfort in an enclosure is disclosed. According to an aspect of the present invention, a method, implemented in a computing device, for numerically evaluating thermal comfort in an enclosure having a non-uniform thermal environment, includes performing a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment based on a given set of boundary conditions for the uniform thermal environment using a numerical analysis tool in the computing device to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin.

The method also includes performing a numerical analysis on the enclosure including one or more thermal manikins in the non-uniform thermal environment based on a set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins. Further, the method includes computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the obtained h_{cal}, the obtained $q"_T$, and an associated surface temperature of the body part using a numerical thermal comfort analysis module in the computing device. Moreover, the method includes evaluating thermal comfort in the enclosure based on the computed t_{eq} of each body part using the numerical thermal comfort analysis module.

According to another aspect of the present invention, an article includes a storage medium having instructions, that when executed by a computing device, result in execution of the method described above.

According to yet another aspect of present invention, a system for numerically evaluating thermal comfort in an enclosure having a non-uniform thermal environment includes multiple client devices, a computer network, and a remote server coupled to the multiple client devices via the computer network. The remote server includes a processor and memory. The memory includes a numerical analysis tool and a numerical thermal comfort analysis module. One of the client devices accesses the numerical analysis tool via the computer network and performs a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment using a given set of boundary conditions for the uniform thermal environment to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin.

The one of the client devices using the numerical analysis tool further performs a numerical analysis on the enclosure including one or more thermal manikins in the non-uniform thermal environment using a set of boundary conditions for the non-uniform thermal environment to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins. Then, the processor using the numerical thermal comfort analysis module computes an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment using the obtained h_{cal}, the obtained $q"_T$, and an associated surface temperature of the body part. Additionally, the processor using the numerical thermal comfort analysis module evaluates the thermal comfort in the enclosure based on each computed t_{eq} and outputs results of the evaluation on a display device of the one of the client devices.

The methods, systems and apparatuses disclosed herein may be implemented in any means for achieving various aspects, and other features will be apparent from the accompanying drawings and from the detailed description that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

Various preferred embodiments are described herein with reference to the drawings, wherein:

FIG. **1** illustrates a schematic representation of a comparison of a non-uniform thermal environment with a uniform thermal environment having same total dry heat loss using an equivalent temperature (t_{eq}) approach, according to an embodiment of the invention.

FIG. **2** illustrates a schematic diagram of a calibration enclosure including a thermal manikin, according to an embodiment of the invention.

FIG. **3** illustrates a schematic diagram of an enclosure including thermal manikins, according to an embodiment of the invention.

FIGS. **4**A and **4**B illustrate an exemplary thermal comfort assessment of an enclosure using thermal comfort diagrams with solar load and no solar load configurations for the enclosure.

FIG. **5** illustrates a process flowchart of an exemplary method of numerically evaluating thermal comfort inside an enclosure having a non-uniform thermal environment, according to an embodiment of the invention.

FIG. **6** is a diagrammatic system view of a data processing system in which any of the embodiments disclosed herein may be performed, according to an embodiment of the invention.

The drawings described herein are for illustration purposes only and are not intended to limit the scope of the present disclosure in any way.

DETAILED DESCRIPTION

A system and method for numerically evaluating thermal comfort inside an enclosure is disclosed. In the following detailed description of the embodiments of the invention, reference is made to the accompanying drawings that form a part hereof, and in which are shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

In the document, the term "calibration enclosure" refers to an enclosure to be calibrated. The terms "uniform thermal environment" and "homogeneous environment" are used interchangeably throughout the document. Also, the terms "non-uniform thermal environment", "actual environment" and "non-homogeneous environment" are used interchangeably throughout the document. Further, the terms "computer network" and "network" are used interchangeably throughout the document. Furthermore, the terms "total dry heat loss" and "total heat flux" are used interchangeably throughout the document.

FIG. **1** illustrates a schematic representation **100** of a comparison of a non-uniform thermal environment **110** with a uniform thermal environment **120** having same total dry heat loss using an equivalent temperature (t_{eq}) approach, according to an embodiment of the invention. The non-uniform thermal environment **110** is an actual environment inside an enclosure which is influenced by parameters such as air velocities, temperatures inside the enclosure, and solar irradiation. Whereas, the uniform thermal environment **120** is an environment inside an imaginary enclosure in which air velocity is approximately equal to zero ($v_a \approx 0$ m/s), temperatures inside the enclosure are constant and which is not exposed to solar irradiation.

In the t_{eq} approach, it is assumed that total dry heat loss (R+C) from an occupant is equal in both the non-homogeneous environment **110** and the homogeneous environment **120**. The total dry heat loss is calculated according to the formula:

$$R+C=h_r\cdot(t_s-\overline{t_r})+h_c\cdot(t_s-t_a),$$

where, R is the radiative heat loss, C is the convective heat loss, t_a is the ambient air temperature (in ° C./K), $\overline{t_r}$ is the mean radiant temperature of the uniform thermal environment and the non-uniform thermal environment (in ° C./K), t_s is the surface temperature of the occupant (e.g., 34° C. as per Human Thermoregulatory System), h_c is the convective heat transfer coefficient (in W/m$^{2\circ}$ C.), and h_r is the radiative heat transfer coefficient (in W/m$^{2\circ}$ C.).

Further, an equivalent temperature (t_{eq}) is defined as a temperature of the uniform thermal environment **120** with the mean radiant temperature ($\overline{t_r}$) equal to the ambient air temperature (t_a) and still air in which the occupant has the same heat exchange by convection and radiation as in the non-uniform thermal environment **110**. Thus, by definition of t_{eq}, the equation for total dry heat loss in the uniform thermal environment **120** can be written as:

$$R+C=h_r\cdot(t_s-t_{eq})+h_c\cdot(t_s-t_{eq}),$$

solving for t_{eq}, using the above-mentioned equations, yields:

$$t_{eq}=\frac{h_r\cdot\overline{t_r}+h_c\cdot t_a}{h_r+h_c}=t_s-\frac{R+C}{h_r+h_c}$$

Based on the above, the present invention provides a method to numerically evaluate thermal comfort in an enclosure having a non-homogeneous environment. Further, the method and system for evaluating the thermal comfort in the enclosure having the non-homogeneous environment is described in the description that follows.

FIG. **2** illustrates a schematic diagram **200** of a calibration enclosure **210** including a thermal manikin **220**, according to an embodiment of the invention. Particularly, FIG. **2** shows the calibration enclosure **210** including the thermal manikin **220** with a uniform thermal environment (e.g., the uniform thermal environment **120** of FIG. **1**). In one embodiment, a computational mesh for the calibration enclosure **210** including the thermal manikin **220** is formed by generating a plurality of cells, where each cell includes multiple nodes. For example, the computational mesh may be a 2D computational mesh or a 3D computational mesh. Further, the 2D/3D computational mesh may be structured, unstructured, or hybrid in type. It is appreciated that, the hybrid computational mesh is a combination of the structured computational mesh and the unstructured computational mesh.

The thermal manikin **220** inside the calibration chamber **210** is a dummy doll formed for reproducing thermal characteristics of an occupant. The thermal manikin **220** is segregated into various body parts substantially simultaneously to the formation of the calibration enclosure **210**. In one embodiment, the segregation of the thermal manikin **220** into various body parts is performed based on a desired thermal comfort resolution. Exemplary body parts of the thermal manikin **220** may include lower left arm, lower right arm, upper left arm, upper right arm, left calf, right calf, left thigh, right thigh, chest, face, left foot, right foot, left hand, and right hand.

In some embodiments, a numerical analysis is performed on the computational mesh to obtain fluid flow and heat

transfer parameters for each cell of the calibration enclosure **210**. In these embodiments, the numerical analysis is performed based on a given set of boundary conditions for the uniform thermal environment. Exemplary parameters that define the given set of boundary conditions include inlet parameters, thermal manikin body surface parameter, enclosure wall parameters, thermal manikin clothing parameters and outlet parameters.

The inlet parameters may include inlet velocity (e.g., reference numeral **230**), inlet flow temperature, and turbulence parameters (e.g., turbulent intensity, turbulent viscosity ratio, etc.). The thermal manikin body surface parameter may be a thermal manikin body surface temperature. The enclosure wall parameters may include wall temperature, and wall surface and material properties. The thermal manikin clothing parameters may include clothing thickness and cloth thermal conductivity. The outlet parameters may include outlet pressure (e.g., reference numeral **240**), back flow total temperature, and back flow turbulence parameters (e.g., back flow turbulent intensity, back flow turbulent viscosity ratio, etc.).

Further, a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin **220** is computed based on the obtained fluid flow and heat transfer parameters for each associated cell. In one embodiment, h_{cal} for each body part is computed according to the formula:

$$h_{cal} = \frac{q''_{T,cal}}{t_s - t_a},$$

where, $q''_{T,cal}$ is the total dry heat loss for each body part of the thermal manikin **220** in the uniform thermal environment, t_s is the surface temperature of the thermal manikin **220** in the uniform thermal environment, and t_a is the ambient air temperature inside the calibration enclosure **210**. This h_{cal} for each body part of the thermal manikin **220** in the calibration enclosure **210** is then used to compute an equivalent temperature (t_{eq}) of each body part of one or more thermal manikins (e.g., the thermal manikins **320** and **330** of FIG. **3**) in a non-uniform thermal environment (e.g., an environment in which thermal comfort is assessed).

FIG. **3** illustrates a schematic diagram **300** of an enclosure **310** including thermal manikins **320** and **330**, according to an embodiment of the invention. Particularly, FIG. **3** shows the enclosure **310** including the thermal manikins **320** and **330** in a non-uniform thermal environment (e.g., the non-uniform thermal environment **110** of FIG. **1**). For example, the enclosure **310** may be an actual enclosure, such as an aircraft, a vehicle (e.g., automotive, train, etc.), or a building, exposed to non-uniform/actual environmental conditions. In one embodiment, a computational mesh for the enclosure **310** including the thermal manikins **320** and **330** is formed by generating a plurality of cells, where each cell includes multiple nodes. For example, the computational mesh may be a 2D computational mesh or a 3D computational mesh. The 2D/3D computational mesh may be a structured, unstructured, or hybrid in type. It is appreciated that, the hybrid computational mesh is a combination of the structured computational mesh and the unstructured computational mesh.

Further, the thermal manikins **320** and **330** inside the enclosure **310** are segregated into various body parts substantially simultaneously to the formation of the enclosure **310**. In one embodiment, the segregation of the thermal manikins **320** and **330** into various body parts is performed based on a desired thermal comfort resolution. Exemplary body parts of the thermal manikins **320** and **330** may include lower left arm, lower right arm, upper left arm, upper right arm, left calf, right calf, right thigh, left thigh, chest, face, left foot, right foot, left hand, and right hand. It is appreciated that the thermal manikins **320** and **330** are exemplary embodiments of the thermal manikin **220** of FIG. **2**.

In some embodiments, a numerical analysis is performed on the computational mesh for obtaining fluid flow and heat transfer parameters for each cell of the enclosure **310**. In these embodiments, the numerical analysis is performed based on a set of boundary conditions for the non-uniform thermal environment. Exemplary parameters that define the set of boundary conditions include inlet parameters, thermal manikin body surface parameter, enclosure wall parameters, semi transparent wall parameters (in case semi transparent walls are present in the enclosure **310**), thermal manikin clothing parameters and outlet parameters.

The velocity inlet parameters may include inlet velocity, inlet flow temperature, and turbulence parameters (e.g., turbulent intensity, turbulent viscosity ratio, etc.). The thermal manikin body surface parameter may be a thermal manikin body surface temperature. The enclosure wall parameters may include a wall temperature, and wall surface and material properties. The semi transparent wall parameters may include semi transparent wall temperature, radiative properties of the wall, and direction and magnitude of solar flux incidence. The thermal manikin clothing parameters may include clothing thickness and cloth thermal conductivity. The outlet parameters may include outlet pressure, back flow total temperature, and back flow turbulence parameters (e.g., back flow turbulent intensity, back flow turbulent viscosity ratio, etc.).

Further, a total heat flux (q''_T) for each body part of the thermal manikins **320** and **330** is computed based on the obtained fluid flow and heat transfer parameters for each associated cell in the non-uniform thermal environment. In one embodiment, the total heat flux (q''_T) for each body part of the thermal manikins **320** and **330** is computed according to the formula:

$$q''_T = h_f(t_w - t_f) + q_{rad},$$

where, h_f is the fluid side local heat transfer coefficient, t_w is the wall surface temperature, t_f is the local fluid temperature, and q_{rad} is the radiative heat flux.

Then, t_{eq} of each body part of the thermal manikins **320** and **330** in the non-uniform thermal environment is computed using the obtained associated h_{cal} and the obtained associated q''_T. In one embodiment, t_{eq} of each body part of the thermal manikin **320** and **330** is computed according to the formula:

$$t_{eq} = t_s - \frac{q''_T}{h_{cal}},$$

where, t_s is the associated surface temperature of the body part.

Moreover, thermal comfort in the enclosure **310** having the non-uniform thermal environment is evaluated based on the each computed t_{eq}. In one exemplary implementation, the thermal comfort in the enclosure **310** is evaluated using the computed t_{eq} for each body part and a thermal comfort diagram. The thermal comfort diagram may be based on international standards (ISO 14505-2) for the type of enclosure **310** (e.g., an aircraft, a building, a vehicle and the like). Moreover, assessment of the thermal comfort in the enclosure **310** using the thermal comfort diagram is discussed in greater detail in FIGS. **4**A and **4**B.

FIGS. **4**A and **4**B illustrate an exemplary thermal comfort assessment of the enclosure **310** using thermal comfort diagrams for solar load and no solar load configurations for the enclosure **310**. It is appreciated that, the thermal comfort diagrams **400** and **450** are formed using t_{eq} limits associated with comfort zone levels of each body part.

Particularly, FIG. **4**A illustrates assessment of thermal comfort when the enclosure **310** is exposed to solar irradiation (e.g., solar load). As illustrated, the computed t_{eq} of each body part is compared with t_{eq} limits defined for the associated body part in the thermal comfort diagram **400**. It can be seen in FIG. **4**A that, the body parts, upper right arm, right calf, chest, right foot, and left hand lie outside the comfort zone. As illustrated, the t_{eq} for the upper right arm, right calf, chest, and right foot falls above the too warm region while the t_{eq} for the left hand lies below the too cold region.

FIG. **4**B illustrates assessment of thermal comfort when the enclosure **310** is not exposed to solar irradiation (e.g., no solar load). As illustrated, the computed t_{eq} of each body part is compared with t_{eq} limits defined for the associated body part in the thermal comfort diagram **450**. It can be seen in FIG. **4**B that, the computed t_{eq} of all the body parts of the thermal manikins **320** and **330** is within the comfort zone except the computed t_{eq} of the upper left arm and the right foot. As illustrated, the t_{eq} of the upper left arm is below the too cold region while the t_{eq} of the right foot is above the too warm region. One skilled in the art will realize that the thermal comfort diagrams **400** and **450** provide a clear representation of a thermal state of an occupant inside an enclosure and can be efficiently used for assessing thermal comfort inside the enclosure **310**.

FIG. **5** illustrates a process flowchart **500** of an exemplary method of numerically evaluating thermal comfort inside an enclosure having a non-uniform thermal environment, according to an embodiment of the invention. In operation **510**, a numerical analysis is performed on a calibration enclosure including a thermal manikin in a uniform thermal environment to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin. In one embodiment, the numerical analysis is performed based on a given set of boundary conditions for the uniform thermal environment using a numerical analysis tool.

In operation **520**, a numerical analysis is performed on an actual enclosure (e.g., building, aircraft, vehicle, etc.) including one or more thermal manikins in the non-uniform thermal environment to obtain a total heat flux (q''_T) for each body part of the one or more thermal manikins. In one embodiment, the numerical analysis is performed based on a set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool.

In operation **530**, an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment is computed (e.g., using a numerical thermal comfort analysis module). In some embodiments, t_{eq} is computed based on the obtained associated h_{cal}, the obtained associated q''_T, and an associated surface temperature of the body part. In operation **540**, thermal comfort in the enclosure is evaluated (e.g., using the numerical thermal comfort analysis module) based on each computed t_{eq}.

FIG. **6** is a diagrammatic system view **600** of a data processing system in which any of the embodiments disclosed herein may be performed, according to an embodiment of the invention. Particularly, the diagrammatic system view **600** of FIG. **6** illustrates a remote server **602** which includes a processor **604** and memory **606**, client devices **608**, and a computer network **610**. The diagrammatic system view **600** also illustrates main memory **612**, static memory **614**, a bus **616**, a video display **618**, an alpha-numeric input device **620**, a cursor control device **622**, a drive unit **624**, a signal generation device **626**, a network interface device **628**, a machine readable medium **630**, a numerical analysis tool **632** (e.g., a mesh generator and finite volume solver), and a numerical thermal comfort analysis module **634**.

The diagrammatic system view **600** may indicate a computing device and/or a data processing system in which one or more operations disclosed herein are performed. The remote server **602** may be a server coupled to the client devices **608** via the computer network **610**. The remote server **602** may provide access to the numerical analysis tool **632** and the numerical thermal comfort analysis module **634** to the client devices **608** via the computer network **610**. The processor **604** may be a microprocessor, a state machine, an application specific integrated circuit, a field programmable gate array, etc.

The memory **606** may be a non volatile memory that is temporarily configured to store a set of instructions associated with the numerical analysis tool **632** and the numerical thermal comfort analysis module **634**. The client devices **608** may be multiple computer devices coupled to the remote server **602** via the computer network **610** for numerically evaluating thermal comfort in an enclosure (e.g., the enclosure **310** of FIG. **3**) having a non-uniform thermal environment. The main memory **612** may be dynamic random access memory and/or primary memory. The static memory **614** may be a hard drive, a flash drive, and/or other memory associated with the data processing system.

The bus **616** may be an interconnection between various circuits and/or structures of the data processing system. The video display **618** may provide graphical representation of information on the data processing system. The alpha-numeric input device **620** may be a keypad, keyboard and/or any other input device of text. The cursor control device **622** may be a pointing device such as a mouse. The drive unit **624** may be a hard drive, a storage system, and/or other longer term storage subsystem.

The signal generation device **626** may be a basic input/output system (BIOS) and/or a functional operating system of the data processing system. The network interface device **628** may perform interface functions (e.g., code conversion, protocol conversion, and/or buffering) required for communications to and from the network **610** between multiple client devices **608** and the remote server **602**. The machine readable medium **630** may provide instructions (e.g., associated with the numerical analysis tool **632** and the numerical thermal comfort analysis module **634**) on which any of the methods disclosed herein may be performed. The numerical analysis tool **632** and the numerical thermal comfort analysis module **634** may provide source code and/or data code to the processor **604** to enable any one or more operations disclosed herein.

For example, a storage medium (e.g., the machine readable medium **630**) has instructions, that when executed by a computing platform (e.g., the processor **604**), result in execution of a method for numerically evaluating thermal comfort in an enclosure having a non-uniform thermal environment (e.g., the enclosure **310** of FIG. **3**). The method includes performing a numerical analysis on a calibration enclosure (e.g., the enclosure **210** of FIG. **2**) including a thermal manikin (e.g., the thermal manikin **220** of FIG. **2**) in a uniform thermal environment using the numerical analysis tool **632** to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin. In one example embodiment, the thermal manikin may include body parts segregated based on a

desired thermal comfort resolution. The method also includes performing a numerical analysis on an actual enclosure including one or more thermal manikins (e.g., the thermal manikins **320** and **330** of FIG. **3**) in the non-uniform thermal environment using the numerical analysis tool **632** to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins.

The method further includes computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the obtained associated h_{cal}, the obtained associated $q"_T$, and an associated surface temperature of the body part using the numerical thermal comfort analysis module **634**. Moreover, the method includes evaluating the thermal comfort in the enclosure based on each computed t_{eq} using the numerical thermal comfort analysis module **634**.

For performing the numerical analysis on the calibration enclosure, in one embodiment, the storage medium **630** may have instructions to generate a computational mesh (e.g., 2D or 3D) of the calibration enclosure including the thermal manikin in the uniform thermal environment using the numerical analysis tool **632**. For example, the computational mesh may include a plurality of cells and each cell includes multiple nodes.

Further, the storage medium **630** may have instructions to perform a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on a given set of boundary conditions for the uniform thermal environment using the numerical analysis tool **632**. The storage medium **630** may also have instructions to compute h_{cal} for each body part based on the obtained fluid flow and heat transfer parameters for each associated cell using the numerical analysis tool **632**.

Further, for performing the numerical analysis on the enclosure, the storage medium **630** may have instructions to generate a computational mesh of the enclosure including the one or more thermal manikins in the non-uniform thermal environment using the numerical analysis tool **632**. For example, the computational mesh may include a plurality of cells and each cell includes multiple nodes.

The storage medium **630** may also have instructions to perform a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on a set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool **632**. Further, the storage medium **630** may have instructions to compute $q"_T$ for each body part of the one or more thermal manikins based on the obtained fluid flow and heat transfer parameters for each associated cell in the non-uniform thermal environment using the numerical analysis tool **632**.

In accordance with the above described embodiments, one of the client devices **608** accesses the numerical analysis tool **632** via the computer network **610**. Further, the one of the client devices **608** performs the numerical analysis on the calibration enclosure including the thermal manikin in the uniform thermal environment to obtain h_{cal} for each body part of the thermal manikin using the numerical analysis tool **632**. Then, the one of the client devices **608** performs the numerical analysis on an actual enclosure including one or more thermal manikins in the non-uniform thermal environment to obtain $q"_T$ for each body part of the one or more thermal manikins using the numerical analysis tool **632**.

The processor **604** then computes t_{eq} of each body part of the one or more thermal manikins using the obtained associated h_{cal}, the obtained associated $q"_T$, and an associated surface temperature of the body part using the numerical thermal comfort analysis module **634**. Based on each computed t_{eq}, the processor **604** evaluates thermal comfort in the actual enclosure using the numerical thermal comfort analysis module **634**. The processor **604** then displays results of evaluation of thermal comfort on a display device (e.g., the video display **618**) of the one of the client devices **608**.

In the one exemplary implementation, thermal comfort assessment in a cockpit of an aircraft having a non-uniform thermal environment is performed using the above-described systems and methods. For numerically evaluating thermal comfort inside the cockpit of the aircraft, the one of the client devices **608** generates a computational mesh of a calibration enclosure (e.g., the calibration enclosure **210** of FIG. **2**) including a thermal manikin in a uniform thermal environment using the numerical analysis tool **632**. Then, the one of the client devices **608** performs a numerical analysis on the generated computational mesh using the numerical analysis tool **632** to obtain fluid flow and heat transfer parameters for each cell of the computational mesh. Based on the obtained fluid flow and heat transfer parameters, the processor **604** computes h_{cal}, for each body part of the thermal manikin.

Following this, the one of the client devices **608** generates a computational mesh of the cockpit of the aircraft having similar thermal manikins (e.g., pilots) using the numerical analysis tool **632**. In one embodiment, the following is considered while generating the computational mesh:

- Surface mesh is sufficiently refined in regions such as inlets, sharp, corners, pilots and the like.
- Boundary layers are generated at all surfaces to capture correct Y^+ values (e.g., a non-dimensional wall distance for a wall-bounded flow).
- Volume mesh is refined in inlet jet regions.

Then, the one of the client devices **608** performs a numerical analysis on the cockpit using the numerical analysis tool **632** to obtain fluid flow and heat transfer parameters for each cell of the cockpit. In one embodiment, the numerical analysis tool **632** performs the numerical analysis on the cockpit using a set of boundary conditions for the cockpit. Further, based on the obtained fluid flow and heat transfer parameters, the processor **604** computes $q"_T$ for each body part of the thermal manikins using the numerical analysis tool **632**.

Subsequently, the processor **604** computes t_{eq} of each body part of the thermal manikins based on the obtained associated h_{cal}, the obtained associated $q"_T$ and an associated surface temperature of the body part using the numerical thermal comfort analysis module **634**. Then, the processor **604** evaluates thermal comfort in the cockpit based on each computed t_{eq} using the numerical thermal comfort analysis module **634**. The results of evaluation are then displayed to a user of the one the client devices **608**.

In various embodiments, the above-described technique has been validated by building numerical solutions to evaluate thermal comfort in various types of enclosures under different environmental conditions. The above-described technique is appropriately sensitive to changes in the physical conditions. Further, the above-described technique is completely performed using numerical solutions to reduce dependency on experiments and the like. This helps speed-up development cycle and reduce cost without compromising on the accuracy of determining thermal comfort in an enclosure. Furthermore, the above-described technique evaluates thermal comfort by considering special variations along with the occupant's body to account for variations in the flow and thermal conditions on each body part.

Although, the above-mentioned embodiments are described with respect to a numerical analysis tool to generate a computational mesh and perform numerical analysis on an

enclosure, one can envision that, the computational mesh can be generated separately using a mesh generation tool (e.g., Hypermesh®) and the numerical analysis is performed separately using any numerical analysis tool (e.g., Fluent®).

In addition, it will be appreciated that the various operations, processes, and methods disclosed herein may be embodied in a machine-readable medium and/or a machine accessible medium compatible with a data processing system (e.g., a computer system), and may be performed in any order (e.g., including using means for achieving the various operations). Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A method, implemented in a computing device, for numerically evaluating thermal comfort in an actual enclosure having a non-uniform thermal environment, comprising:

performing a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment based on a given set of boundary conditions for the uniform thermal environment;

performing a numerical analysis on the actual enclosure including one or more thermal manikins in the non-uniform thermal environment based on a set of boundary conditions for the non-uniform thermal environment;

computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the numerical analysis performed in the uniform thermal environment, non-uniform thermal environment, and surface temperature of each body part; and

evaluating the thermal comfort in the actual enclosure based on each computed t_{eq} using a numerical thermal comfort analysis module, wherein parameters that define the set of boundary conditions for the uniform thermal environment and the non-uniform thermal environment are selected from the group consisting of inlet parameters, thermal manikin body surface parameter, enclosure wall parameters, semi transparent wall parameters, thermal manikin clothing parameters and outlet parameters.

2. The method of claim **1**, wherein performing the numerical analysis on the calibration enclosure including the thermal manikin in the uniform thermal environment based on the given set of boundary conditions, comprises:

generating a computational mesh of the calibration enclosure including the thermal manikin in the uniform thermal environment using a numerical analysis tool in the computing device and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes, wherein the thermal manikin includes body parts segregated based on a desired thermal comfort resolution;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the given boundary conditions for the uniform thermal environment using the numerical analysis tool; and

computing a surface heat transfer coefficient (h_{cal}) for each body part based on the obtained fluid flow and heat transfer parameters for each cell using the numerical analysis tool.

3. The method of claim **2**, wherein performing the numerical analysis on the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment based on the set of boundary conditions for the non-uniform thermal environment, comprises:

generating a computational mesh of the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool; and

computing a total heat flux (q''_T) for each body part of the one or more thermal manikins based on the obtained fluid flow and heat transfer parameters for each cell in the non-uniform thermal environment using the numerical analysis tool.

4. The method of claim **3**, wherein computing the equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment comprises:

computing the equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the computed h_{cal}, the computed q''_T, and an associated surface temperature of the body part using the numerical thermal comfort analysis module in the computing device.

5. The method of claim **4**, wherein the computational mesh is selected from the group consisting of 2D computational mesh and 3D computational mesh.

6. The method of claim **4**, wherein the computational mesh is selected from the group consisting of structured, unstructured, and hybrid.

7. The method of claim **1**, wherein the actual enclosure is selected from the group consisting of a building, a vehicle, and an aircraft.

8. The method of claim **1**, wherein the inlet parameters are selected from the group consisting of inlet velocity, inlet flow temperature, and turbulence parameters.

9. The method of claim **1**, wherein the outlet parameters are selected from the group consisting of outlet pressure, back flow total temperature, and back flow turbulence parameters.

10. The method of claim **1**, wherein the enclosure wall parameters comprises a wall temperature, and wall surface and material properties.

11. The method of claim **1**, wherein the semi transparent wall parameters are selected from the group consisting of semi transparent wall temperature, radiative properties of wall, and direction and magnitude of solar flux incidence.

12. The method of claim **1**, wherein the thermal manikin body surface parameter is a thermal manikin body surface temperature.

13. The method of claim **1**, wherein the thermal manikin clothing parameters are selected from the group consisting of clothing thickness and cloth thermal conductivity.

14. A system for numerically evaluating thermal comfort in an actual enclosure having a non-uniform thermal environment, comprising:

multiple client devices;

a computer network; and

a remote server coupled to the multiple client devices via the computer network, wherein the remote server comprises:

a processor; and

memory, wherein the memory includes a numerical analysis tool and a numerical thermal comfort analysis module, wherein one of the client devices accesses the numerical analysis tool via the computer network

and performs a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment using a given set of boundary conditions for the uniform thermal environment to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin, wherein the one of the client devices using the numerical analysis tool further performs a numerical analysis on the actual enclosure including one or more thermal manikins in the non-uniform thermal environment using a set of boundary conditions for the non-uniform thermal environment to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins, wherein the processor using the numerical thermal comfort analysis module computes an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment using the obtained h_{cal}, the obtained $q"_T$, and an associated surface temperature of the body part, and wherein the processor using the numerical thermal comfort analysis module evaluates the thermal comfort in the actual enclosure based on each computed t_{eq} and outputs results of the evaluation on a display device of the one of the client devices.

15. The system of claim **14**, wherein performing the numerical analysis on the calibration enclosure including the thermal manikin in the uniform thermal environment based on the given set of boundary conditions, comprises:

generating a computational mesh of the calibration enclosure including the thermal manikin in the uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes, wherein the thermal manikin includes body parts segregated based on a desired thermal comfort resolution;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the given set of boundary conditions for the uniform thermal environment using the numerical analysis tool; and

computing the surface heat transfer coefficient (h_{cal}) for each body part based on the obtained fluid flow and heat transfer parameters for each cell using the numerical analysis tool.

16. The system of claim **14**, wherein performing the numerical analysis on the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment based on the set of boundary conditions for the non-uniform thermal environment, comprises:

generating a computational mesh of the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool; and

computing the total heat flux ($q"_T$) for each body part of the one or more thermal manikins based on the obtained fluid flow and heat transfer parameters for each cell in the non-uniform thermal environment using the numerical analysis tool.

17. The system of claim **16**, wherein the actual enclosure is selected from the group consisting of a building, a vehicle, and an aircraft.

18. An article, comprising:

a storage medium having instructions, that when executed by a computing device, result in execution of a method for numerically evaluating thermal comfort in an actual enclosure having a non-uniform thermal environment, comprising:

performing a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment based on a given set of boundary conditions for the uniform thermal environment using a numerical analysis tool in the computing device to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin;

performing a numerical analysis on the actual enclosure including one or more thermal manikins in the non-uniform thermal environment based on a set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins;

computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the obtained h_{cal}, the obtained $q"_T$, and an associated surface temperature of the body part using a numerical thermal comfort analysis module in the computing device; and

evaluating the thermal comfort in the actual enclosure based on each computed t_{eq} using the numerical thermal comfort analysis module.

19. The article of claim **18**, wherein performing the numerical analysis on the calibration enclosure including the thermal manikin in the uniform thermal environment based on the given set of boundary conditions, comprises:

generating a computational mesh of the calibration enclosure including the thermal manikin in the uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes, wherein the thermal manikin includes body parts segregated based on a desired thermal comfort resolution;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the given set of boundary conditions for the uniform thermal environment using the numerical analysis tool; and

computing the surface heat transfer coefficient (h_{cal}) for each body part based on the obtained fluid flow and heat transfer parameters for each cell using the numerical analysis tool.

20. The article of claim **18**, wherein performing the numerical analysis on the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment based on the set of boundary conditions for the non-uniform thermal environment, comprises:

generating a computational mesh of the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the set of boundary

conditions for the non-uniform thermal environment using the numerical analysis tool; and

computing the total heat flux ($q"_T$) for each body part of the one or more thermal manikins based on the obtained fluid flow and heat transfer parameters for each cell in the non-uniform thermal environment using the numerical analysis tool.

21. A method, implemented in a computing device, for numerically evaluating thermal comfort in an actual enclosure having a non-uniform thermal environment, comprising:

performing a numerical analysis on a calibration enclosure including a thermal manikin in a uniform thermal environment based on a given set of boundary conditions for the uniform thermal environment using a numerical analysis tool in the computing device to obtain a surface heat transfer coefficient (h_{cal}) for each body part of the thermal manikin;

performing a numerical analysis on the actual enclosure including one or more thermal manikins in the non-uniform thermal environment based on a set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool to obtain a total heat flux ($q"_T$) for each body part of the one or more thermal manikins;

computing an equivalent temperature (t_{eq}) of each body part of the one or more thermal manikins in the non-uniform thermal environment based on the obtained h_{cal}, the obtained $q"_T$, and an associated surface temperature of the body part using a numerical thermal comfort analysis module in the computing device; and

evaluating the thermal comfort in the actual enclosure by comparing each computed t_{eq} with a thermal comfort diagram using the numerical thermal comfort analysis module, wherein the thermal comfort diagram is formed using t_{eq} limits associated with comfort zone levels of each body part.

22. The method of claim **21**, wherein performing the numerical analysis on the calibration enclosure including the thermal manikin in the uniform thermal environment based on the given set of boundary conditions, comprises:

generating a computational mesh of the calibration enclosure including the thermal manikin in the uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes, wherein the thermal manikin includes body parts segregated based on a desired thermal comfort resolution;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the given boundary conditions for the uniform thermal environment using the numerical analysis tool; and

computing the surface heat transfer coefficient (h_{cal}) for each body part based on the obtained fluid flow and heat transfer parameters for each cell using the numerical analysis tool.

23. The method of claim **21**, wherein performing the numerical analysis on the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment based on the set of boundary conditions for the non-uniform thermal environment, comprises:

generating a computational mesh of the actual enclosure including the one or more thermal manikins in the non-uniform thermal environment using the numerical analysis tool and wherein the computational mesh includes a plurality of cells and each cell includes multiple nodes;

performing a numerical analysis on the generated computational mesh to obtain fluid flow and heat transfer parameters for each cell based on the set of boundary conditions for the non-uniform thermal environment using the numerical analysis tool; and manikins based on the obtained fluid flow and heat transfer parameters for each cell in

computing the total heat flux ($q"_T$) for each body part of the one or more thermal the non-uniform thermal environment using the numerical analysis tool.

24. The method of claim **21**, wherein the thermal comfort diagram is based on international standards for a type of the actual enclosure.

25. The method of claim **24**, wherein the type of the actual enclosure is selected from the group consisting of a building, a vehicle, and an aircraft.

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